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IRS OBSERVATIONS OF LMC PLANETARY NEBULA SMP 83

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ABSTRACT

The first observations of the infrared spectrum of the LMC planetary nebula SMP 83 as observed by the recently launched Spitzer Space Telescope are presented. The high resolution ($R \sim 600$) spectrum shows strong emission lines but no significant continuum. The infrared fine structure lines are used, together with published optical spectra, to derive the electron temperature of the ionized gas for several ions. A correlation between the electron temperature with ionization potential is found. Ionic abundances for the observed infrared ions have been derived and the total neon and sulfur abundances have been determined. These abundances are compared to average LMC abundances of H II regions to better understand the chemical evolution of these elements. The nature of the progenitor star is also discussed.

Subject headings: ISM: abundances — ISM: lines and bands — planetary nebulae: individual(SMP 83) — stars: evolution — stars: Wolf–Rayet

1. INTRODUCTION

Stars of low and intermediate mass evolve through the planetary nebula phase. By the ejection of their outer layers the Planetary Nebulae (PNe) contribute to the enrichment of the interstellar medium. Spectroscopic studies of PNe are essential to better understand and quantify this enrichment. Until the launch of the Spitzer Space Telescope it was impossible to fully study PNe in the infrared outside the galaxy's chemical environment because of the faintness of extragalactic targets. Reaching targets in the Large and Small Magellanic Clouds (LMC, SMC) is particularly appealing because they have known distances and arise in a lower metallicity environment than galactic targets. Since the distance is known the enrichment of expelled nebular material can be combined with accurate knowledge of the central star's luminosity.

In this letter, the infrared spectrum of the LMC planetary nebula SMP 83, taken with the IRS[4] spectrograph on board the Spitzer Space Telescope, is presented. The nature of the central star of SMP 83 is not yet well known and has been the subject of several studies. Dopita et al. (1993), using HST imagery, conclude that SMP 83 is a type I PN with a very massive progenitor star of 6 $M_\odot$, close to the progenitor mass limit for a PN. Torres-Peimbert et al. (1993) reported the sudden development of Wolf-Rayet (WR) features in the He II line at λ4686 in the nebula. During 1993 and 1994 the central star experienced an increase in luminosity which was studied by Vassiliadis (1996) and more recently by Hamann et al. (2003). The latter showed that the chemical composition of the atmosphere is that of incompletely processed CNO material. They suggest several scenarios for the nature of the central star, including a low– or high–mass single star or a low– or high–mass binary system. Hamann et al. (2003) conclude that binary systems present the fewest contradictions when explaining all the central star peculiarities. Peña et al. (1995) indicated that the fast variations of the stellar parameters are similar to those expected in the initial phase of the *born–again* scenario in which stars undergo a final helium flash.

Meatheringham and Dopita (1991) presented optical spectroscopy for 30 PNe in the LMC including SMP 83. They found that the densities obtained with the S II lines were slightly lower than those derived with the O II lines. Tsamis et al. (2003) made spectroscopic observations of several galactic and LMC PNe, including SMP 83. Using collisionally excited lines they derived densities, temperatures and ionic abundances for the objects in their sample. Peña & Ruiz (1988) and Peña et al. (1995) combined optical and ultraviolet (IUE) data with ionization models to derive the composition of the nebula. They found that the C and O abundances were under–abundant when compared to H II regions in the LMC. Peña et al. (1995) based on the lack of evidences of freshly synthesized carbon conclude that the third dredge–up did not occur.

For the first time, complete mid–infrared spectra (from 5.3 to 40 μm) for this nebula are available. The infrared region of the spectrum is very useful for several reasons. The lines seen in the infrared are not sensitive to the temperature, making them reliable indicators of the chemical composition of the nebulae. The peak of dust emission occurs in the infrared and features such as PAHs and silicates (when present) can only be studied in this part of the spectrum.

2. OBSERVATIONS AND DATA REDUCTION

The observations were made with the IRS spectrograph (Houck et al. 2004) on board the Spitzer Space Telescope (Werner et al. 2004). The data were obtained during the in-orbit checkout phase of the satellite, on 2003 Nov 9 (observation number 7857664). The diameter of the neb-

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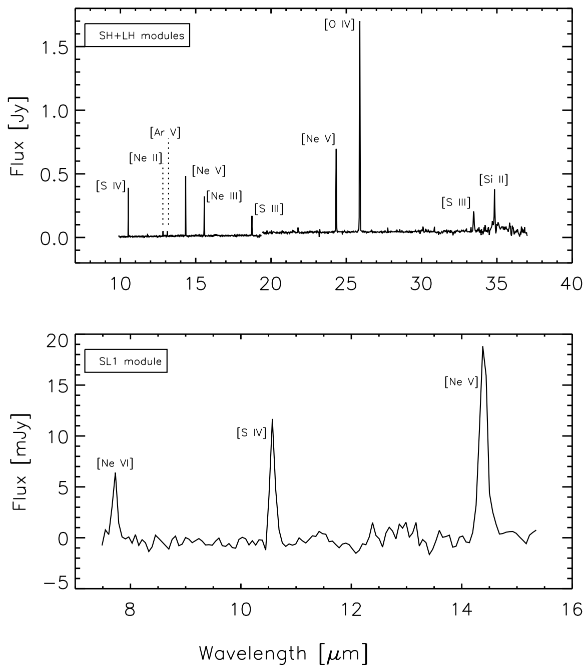

FIG. 1.— High (top) and low (bottom) resolution spectra of LMC planetary nebula SMP 83. Note that the low resolution observation consisted only on the first order of the SL module (7.5–14.2 μm).

ula is $< 2''$ and therefore can be calibrated as a point source.

The observations at SMP 83 consisted of spectra from Short–High (SH), Long-High (LH), and the first order of Short–Low (SL1) modules. The wavelength coverage for each module is; SL1 (from 7.5–14.2 μm), SH (from 10–19.5 μm), LH (from 19.3–37 μm). The high–resolution modules provide a spectral resolution of $\sim$600 and the low–resolution $\sim$90. The "staring" observation mode was used, with two nod positions for each module. The observation times were 180, 240 and 480 seconds for SL1, SH and LH respectively. These total integration times represent the co–addition of shorter individual ramps.

The data were processed through a copy of the Spitzer Science Center's pipeline reduction software (version S9.1) maintained at Cornell. From that point the reduction and extraction techniques were carried out as follows: The mean of the flux estimates from each ramp cycle were combined. The two nod positions in SL1 were subtracted to eliminate the contribution from the background. The resulting images were extracted using the Cornell-developed software package SMART (Higdon et al. 2004). The high–resolution spectra were calibrated by dividing the extracted spectrum of the source by the spectrum of the standard star HR 6348 (observation number 7834624) and multiplying by its template (Cohen et al. 2003). Remaining spikes were removed manually. The resulting spectra in SH and LH at the second nod position are shown in Figure 1. The quality of the spectra are remarkable; it is the first detection of these lines in an extragalactic PN. Due to a mispointing the SH observation at the first nod position was not used in the analysis of the data.

TABLE 1
MEASURED FLUXES IN THE HIGH RESOLUTION SPECTRA AND CALCULATED IONIC ABUNDANCES (RELATIVE TO HYDROGEN).

λ	Ident.	Flux[a]		$N_{\rm ion}/N_{\rm p}$
[μm]		Observed	De-reddened	($\times 10^{-5}$)
7.652[b]	[Ne VI]	8.53	8.56	1.09
10.52	[S IV]	14.7	15.9	0.19
12.82	[Ne II]	1.55	1.56	1.15
13.11	[Ar V]	1.23	1.24	0.02
14.33	[Ne V]	14.2	14.3	1.14
15.55	[Ne III]	10.3	10.4	3.72
18.73	[S III]	3.92	3.94	0.22
24.33	[Ne V]	15.0	15.1	1.26
25.89	[O IV]	43.7	43.9	6.08
33.46	[S III]	3.47	3.48	0.36
34.84	[Si II]	2.76	2.77	0.56

[a]In units of 10^{-14} erg cm^{-2}s^{-1}.
[b]Measured from the low resolution spectrum and scaled so that the S IV and Ne V lines measured in SL1 (module which was reduced and calibrated with SMART software) matched those fluxes in SH.

3. ANALYSIS OF THE EMISSION LINES

The measured lines are listed in the third column of Table 1. Several calibration and cross-check techniques were applied to the data. A comparison of the measured fluxes using these different techniques leads us to conclude that the uncertainty in the absolute flux is 20–25%. The only exceptions are [Ne VI] (this line is measured at the edge of the spectrum in SL1 and is noisy) and the [Si II] lines with uncertainties of 50% and 30% respectively. Absolute flux calibration of the IRS instrument is ongoing and these uncertainties will decrease with improved future reductions. The fine structure lines provide information of the ionic abundances in the nebula, after the electron density and temperature are determined. Although the extinction correction in the infrared is small the lines have been corrected for extinction using $C(H\beta) = 0.15$ (Meatheringham and Dopita 1991; Dopita et al. 1993) and are given in column 4 of Table 1.

3.1. *Electron density and temperature*

Intensity ratios of lines originating from levels close in energy are needed to derive the electron density $N_{\rm e}$. Two lines of the same ion have been observed for Ne V and S III. However, these ions are sensitive to densities from $\sim$3000 to $\sim$10^5 cm^{-3} and the observed ratios for both ions indicate that the density for this nebula is lower than 3000 cm^{-3}. Meatheringham and Dopita (1991) using O II and S II ratios (which are sensitive to lower density regimes) derived densities of 2470 and 2220 cm^{-3} respectively. Tsamis et al. (2003) obtain electron densities of 1900 cm^{-3} and 5700 cm^{-3} for respectively S II and Ar IV. We have adopted for our calculations an average of those given by Meatheringham and Dopita (1991) ($N_{\rm e}$=2350 cm^{-3}). This density is low enough than the critical density of all the lines listed in Table 1 (except for the 33.4 and 34.8 μm lines) and therefore does not affect the line intensities. If an average density of all the values given above is adopted (3000 cm^{-3}) none of the conclusions would be affected.

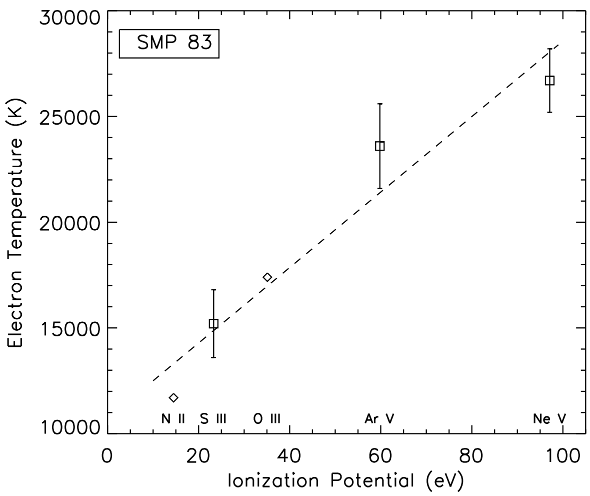

Fig. 2.— Derived electron temperature versus the ionization potential require to reach the respective ionization level. The diamonds are the T_e derived by Meatheringham and Dopita (1991, see text) and the squares those derived in this letter.

To derive the electron temperature T_e ratios of lines originating from energy levels that differ by several electron volts are needed. We combine line strengths from our spectra with optical lines given by Meatheringham and Dopita (1991) to increase the numbers of ions available to derive T_e. Meatheringham and Dopita (1991) derived T_e=17 400 K for O III and T_e=11 700 K for N II using the ratio of optical lines. Their optical measurements together with the infrared lines allow us to derive the temperature for three more ions, S III, Ar III, and Ne V. The ratios used are; 18.7 μm/6312 Å and 33.4 μm/6312 Å for S III, 13.1 μm/7006 Å for Ar V, and 14.3 μm/3426 Å and 24.3 μm/3426 Å for Ne V. These temperatures together with those by Meatheringham and Dopita (1991) are presented in Figure 2 versus the Ionization Potential (IP). The Ne V temperature shown in Figure 2 is an average of that found with the 14.3 μm/3426 Å and 24.3 μm/3426 Å ratio. The electron temperature clearly increases with IP and reaches very high values. The dashed line in the figure represents the least–squares fit to the data. High stages of ionization are probably formed close to the central star where the density of harder UV photons is higher, whereas low stages of ionization are probably located further away from the central star, thus giving lower temperatures. This gradient has been observed in several galactic PNe (e.g. Bernard Salas et al. 2001; Pottasch & Beintema 1999), but it is the first time that it is shown for a PN in the LMC. The abundances of the different ions have been calculated using a T_e according to the IP of each ion given by the fit (dashed line) in Figure 2.

3.2. *Ionic abundances*

The ionic abundances have been derived using the dereddened fluxes and N_e and T_e discussed in the previous subsection. These are presented in the last column of Table 1. In order to derive the ionic abundances with respect to hydrogen, we have made use of the observed Hβ flux given by Peña et al. (1994) ($\log(F_{H\beta}) = -12.99$). It is important to notice that Webster (1969) and Meatheringham et al. (1988) give a much different observed value ($\log(F_{H\beta}) = -12.66$). It is unclear why these authors quote such different values. Meatheringham et al. (1988) and Webster (1969) derived the Hβ flux using a filter centered on the line. It may be that they are also measuring part of the stellar flux. Peña et al. (1994) measured the nebular Hβ flux in three different epochs and obtain very similar values (the differences are only due to the smaller slit apertures used). The larger aperture used by Peña et al. (1994) is big enough to contain the nebula. Because of the consistency between the three values they quote and the fact that they separate the contribution from the star and the nebula, we have opted to use that of Peña et al. (1994). The derived T_e in the previous section involves the combination of infrared and optical lines (where the latter are given relative to Hβ=100) and the good agreement seen for all the values supports the choice of the Hβ flux made in this letter. We note however that using the Hβ flux from Webster (1969) or Meatheringham et al. (1988) will bring the ionic abundances derived from the infrared lines down by a factor ∼2.

SMP 83 is a high excitation nebula; several lines have been measured allowing the determination of the ionic abundance of several elements. The O IV abundance is high and is similar to that found by Peña et al. (1995). It accounts for a third part of the total oxygen abundance measured by Peña et al. (1995). Almost all important stages of ionization in neon (except Ne IV) and sulfur (except S II) have been measured. To account for the unobserved stages of ionization the optical lines at λ4729 and λ4728 (for Ne IV) by Tsamis et al. (2003) and at λ6717 and λ6731 (for S II) by Meatheringham and Dopita (1991) have been used. By adding the abundances of different stages of ionization, the total abundances of neon and sulfur are found to be 8.6×10^{-5} and 4.8×10^{-6} respectively. Most of the absolute error in these abundances comes from the uncertainty in the fluxes (Bernard Salas et al. 2003) and therefore the uncertainties in the abundances are ∼35 %.

It is interesting to compare the neon and sulfur abundances to average LMC abundances of H II regions, [S/H]=5.2×10^{-6} and [Ne/H]=5.4×10^{-5} (Vermeij & van der Hulst 2002). Peña et al. (1995) noticed with this comparison that the sulfur and neon abundances they derived where systematically lower than those of the LMC H II regions they compared to. In this paper the sulfur abundance in SMP 83 agrees with that of the LMC. This is important because Marigo et al. (2003) pointed out that the sulfur abundance of the galactic PNe that they studied was lower than solar. They suggested that either the solar sulfur abundance was overestimated or that sulfur could be destroyed in the course of evolution, contrary to evolutionary modeling. Since the sulfur abundance derived in this paper is consistent with that of the LMC, there is support for the hypothesis of an overestimated solar sulfur abundance. It would be interesting to derive the sulfur abundance for more LMC PNe to confirm this. The neon abundance found here is higher than in previous studies (Peña et al. 1995; Dopita et al. 1993; Tsamis et al. 2003). A small part of the difference comes from the ionic abundances

of Ne II and Ne VI whose contributions were neglected in previous studies since it was not observed. Nonetheless, the infrared data show that its contribution to the total neon abundance is important. The larger difference however comes from the contribution from Ne III. In this letter this contribution is found to be 2 times higher than that derived by Tsamis et al. (2003) and Peña et al. (1995) who used the optical lines at 3868 and 3967 Å. This difference is similar to what has been seen in other nebulae (i.e. Pottasch & Beintema 1999; Bernard Salas et al. 2003). The problem depends on the adopted $T_{\rm e}$. The $T_{\rm e}$ obtained when using the ratio of the 15.55 μm and 3869 Å lines is 12 000 K. There are several galactic nebulae for which these lines give a much lower temperature than that of the [O III] lines (i.e., NGC 6302, NGC 6537, NGC 7027). If a higher temperature is used the ionic abundances derived from the optical lines decrease. However the low–level infrared lines are not affected by this problem since they hardly depend on the temperature and give better estimates of the ionic abundance. The neon abundance seems larger than that in the LMC, although this is arguable considering the errors. If real, this enrichment must have taken place likely via α-captures starting from ^{14}N during dredge-up. This mechanism marginalizes the $^{22}{\rm Ne}(\alpha,n)^{25}{\rm Mg}$ reactions expected to occur during thermal pulses, and extinguishes the He-burning shell. This could explain the lack of carbon at the surface of SMP83 (Hamann et al. 2003).

3.3. *Nature of the central star*

A confirmation of the neon enrichment could lead to important constraints in the nature of the progenitor star of SMP 83. In massive stars ($M_{\rm init} > 25 M_{\odot}$), which are convectively unstable, the Ne production occurs through the chain reaction $^{18}{\rm O}(\alpha,n)^{20}{\rm Ne}$ and the observed abundances will depend on whether further α capture through $^{22}{\rm Ne}(\alpha,n)^{26}{\rm Mg}$ has occurred, and on core enrichment from the surface by rotational mixing (Meynet et al. 2003). Neon enhancement in the massive stars thus coincides with carbon and oxygen enhancements and hydrogen depletion in the core. This leads spectroscopically at the surface to WC-type Wolf-Rayet stars, according to the evolutionary models and observational tests of massive stars in early and later post-main sequence stages (Morris et al. 2000, 2004; Dessart et al. 2000). Thus, if the neon enrichment is confirmed, the abundance pattern in the nebula and at the surface of SMP83 most likely excludes the central star as a Population I Wolf-Rayet star, as one of the scenarios proposed by Hamann et al. (2003), and is more consistent with an alternate hypothesis of an intermediate mass star that has experienced efficient dredge-up in the post-AGB phase.

4. SUMMARY AND CONCLUSIONS

Mid infrared spectra of LMC planetary nebula SMP 83 have been presented for the first time using the IRS spectrograph on board the Spitzer Space Telescope. The spectrum of SMP 83 shows high excitation lines and no signs of dust or a continuum associated with the nebula.

The emission lines have been used with optical spectra from the literature to derive the electron temperature for several ions in the nebula. There is a correlation of the electron temperature with ionization potential. The abundances for several ions have been derived. The total neon abundance, with additional contributions from states seen only in the infrared, is higher than the optically-determined abundance, which is more sensitive to the temperature. The neon abundance seems larger than the adopted average neon LMC abundance. This could suggests that some neon enrichment must have taken place in the course of evolution. If the neon enrichment is confirmed, this could favor the scenario of SMP 83 having evolved from an intermediate mass star instead of a massive Wolf–Rayet star as some studies have suggested. The sulfur abundance agrees with that of the LMC. This might indicate that the problem of the low sulfur abundance found in galactic PNe relative to solar comes from an overestimation of the latter, but this should be confirmed with more studies on the sulfur abundance in PNe in the LMC.

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